Biologically-Inspired Intelligent Robots Using Artificial Muscles

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http://ndeaa.jpl.nasa.gov/

Keynote Presentation

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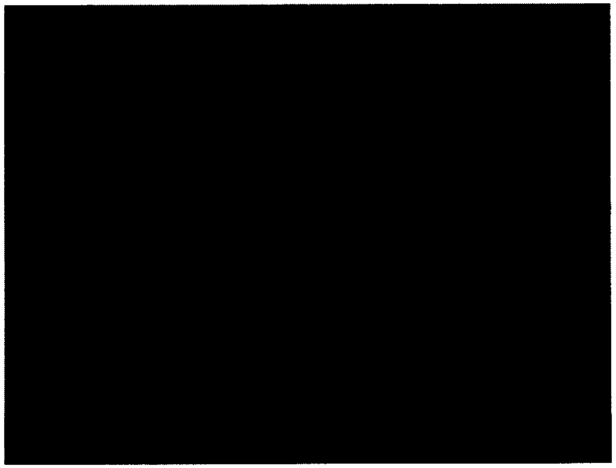
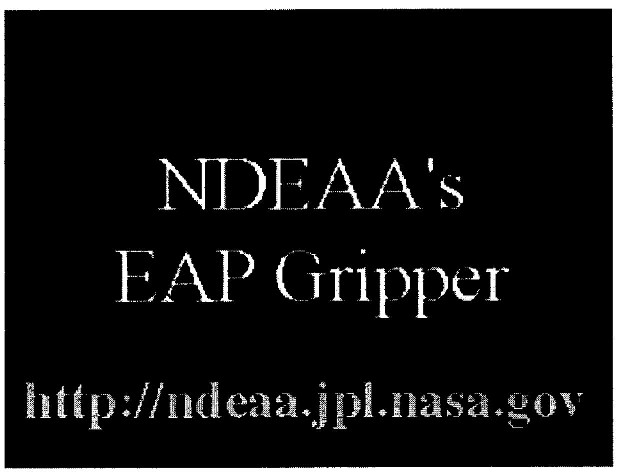
NDEAA Technologies

- **Sensors**
  - USDC as a platform for bit integrated sensors
  - In-process and in-service monitoring (SAW and Bulk Acoustic Wave (BAW) sensors)
- **NDE**
  - Materials properties and flaws characterization using LLW and polar backscattering
- **Ultrasonic Medical Diagnostics and Treatment**
  - High power ultrasound (FMPUL): blood clot lysing, spine trauma and cancer treatment
  - Acoustic Microscopy Endoscope (200MHz)
- **Advanced Actuators**
  - Ultrasonic/Sonic Driller/Corer (USDC) for planetary exploration
  - Ultrasonic motors (USM), Surface Acoustic Wave (SAW) motors and Piezopump
  - Artificial muscles using electroactive polymers
- **Applications: Radiation sources, Robotics, etc.**
  - Ferrosource for multiple radiation types
  - Biomimetics
  - Noninvasive geophysical probing system (NGPS)
  - Multifunction Automated Crawling System (MACS)
  - Adjustable gossamer and membrane structures
  - MEMICA as Haptic interfaces

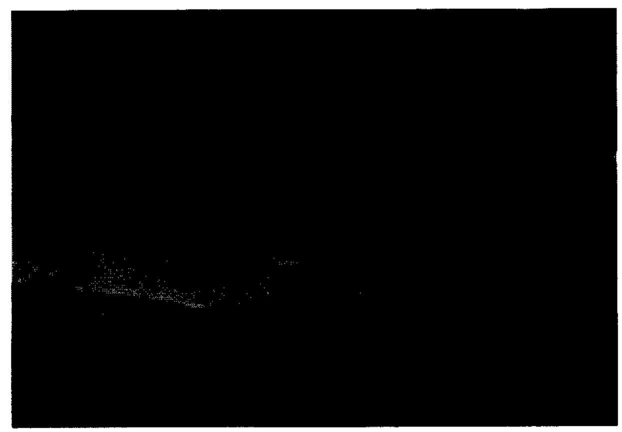
NDEAA related projects


Piezopump

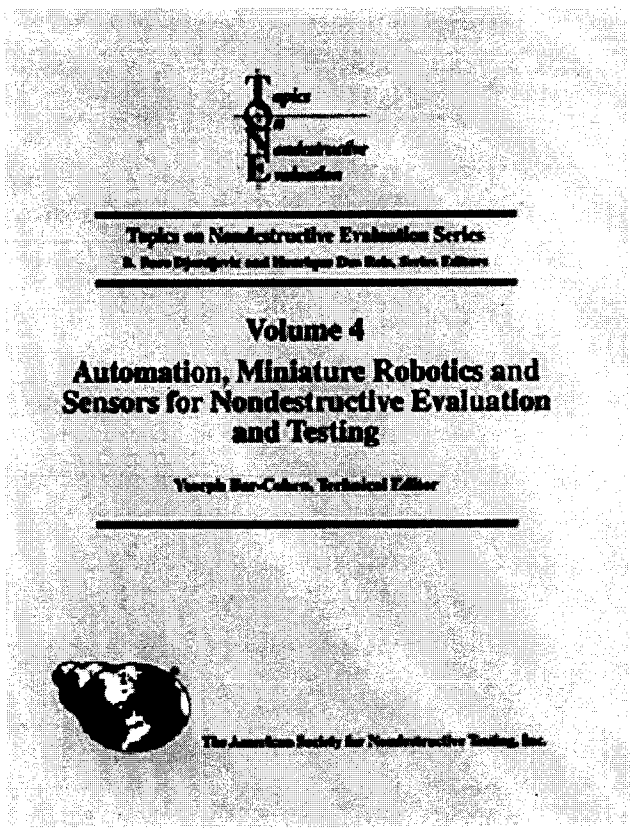

USDC

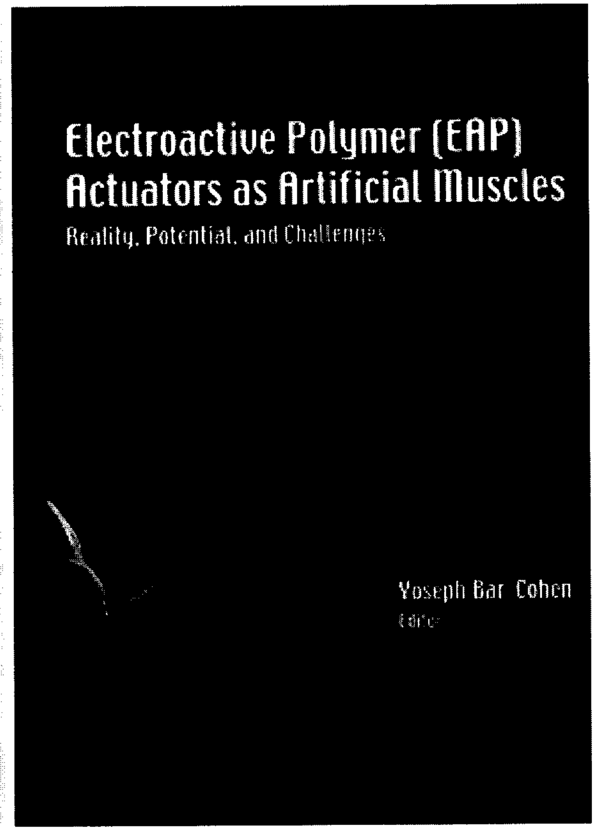


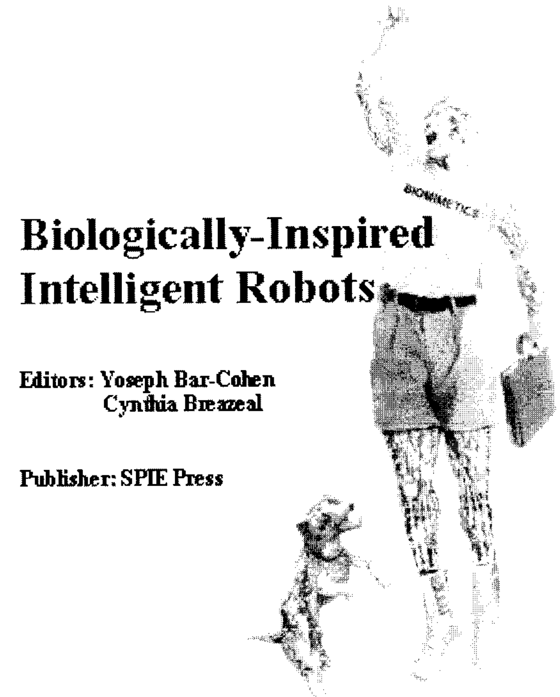
EAP/Artificial Muscles


ERF/MEMICA

Related recent and upcoming books



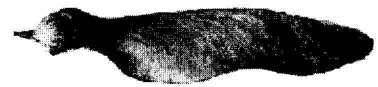




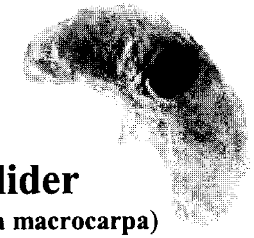
http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm

Nature as a model for robotics engineering

Tumbleweed



Helicopter
(Tipuana tipu)

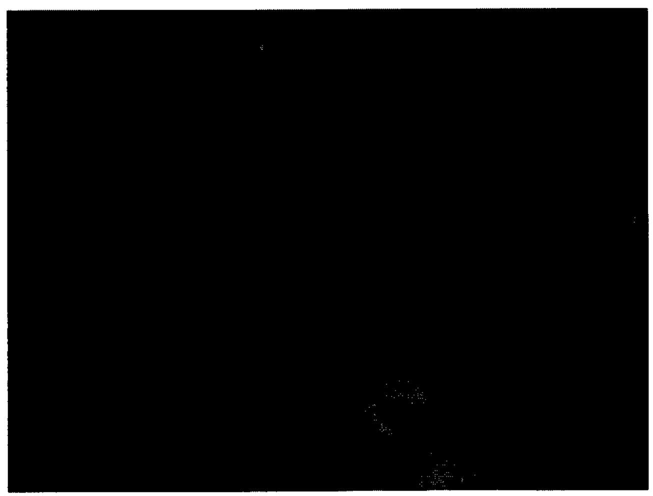


Glider
(Alsomitra macrocarpa)

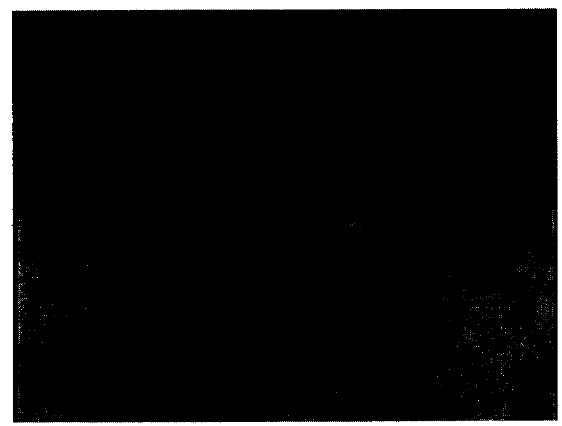
Aerodynamic dispersion of seeds

(Courtesy of Wayne's Word)

Ref: http://waynesword.palomar.edu/plfeb99.htm#helicopters



Courtesy of William M. Kier, of North Carolina



Courtesy of Roger T. Hanlon, Director, Marine Resources Center, Marine Biological Laboratory, Woods Hole, MA

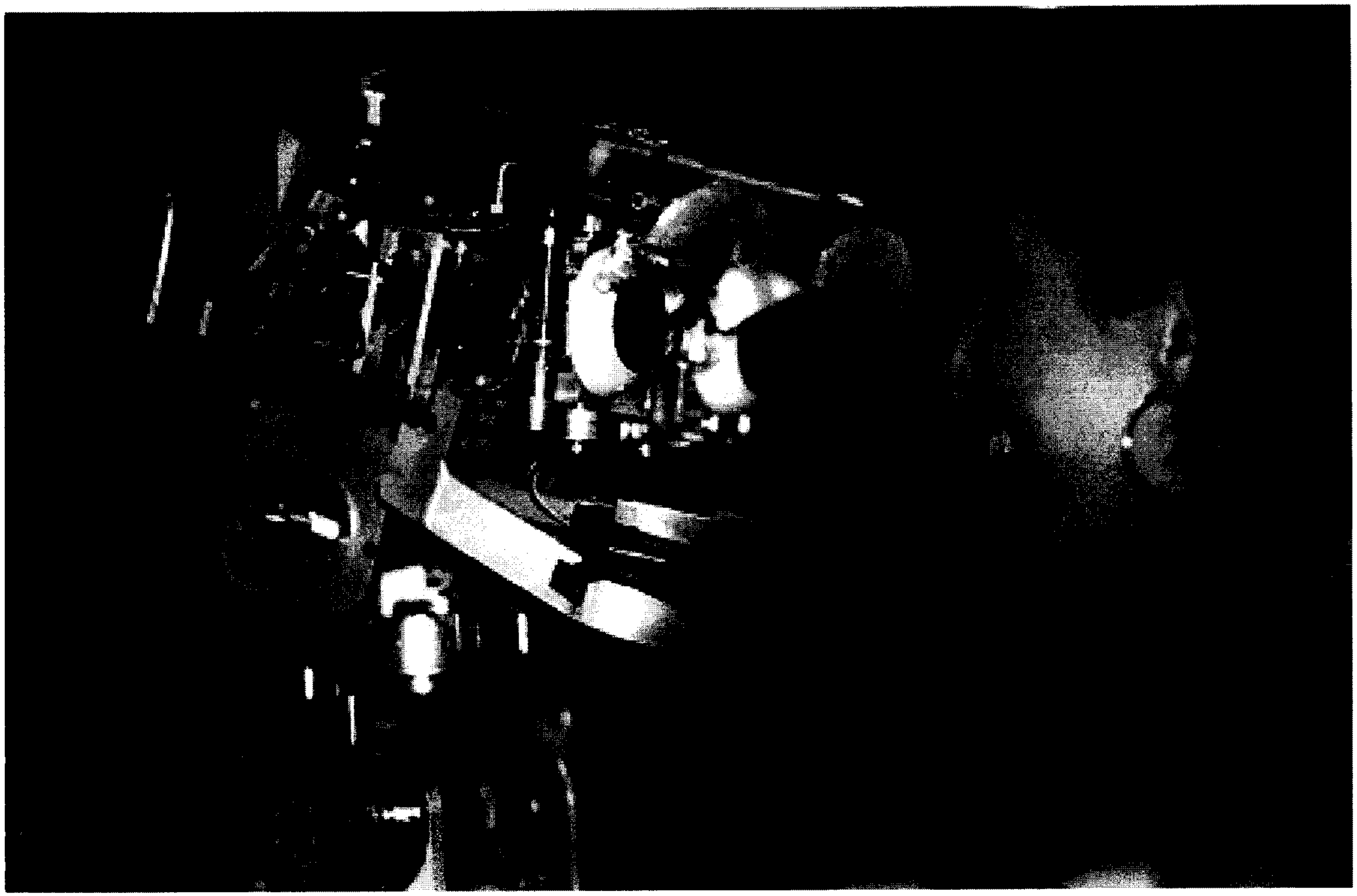
Octopus adaptive shape, texture and camouflage

Ref: http://www.pbs.org/wnet/nature/octopus/

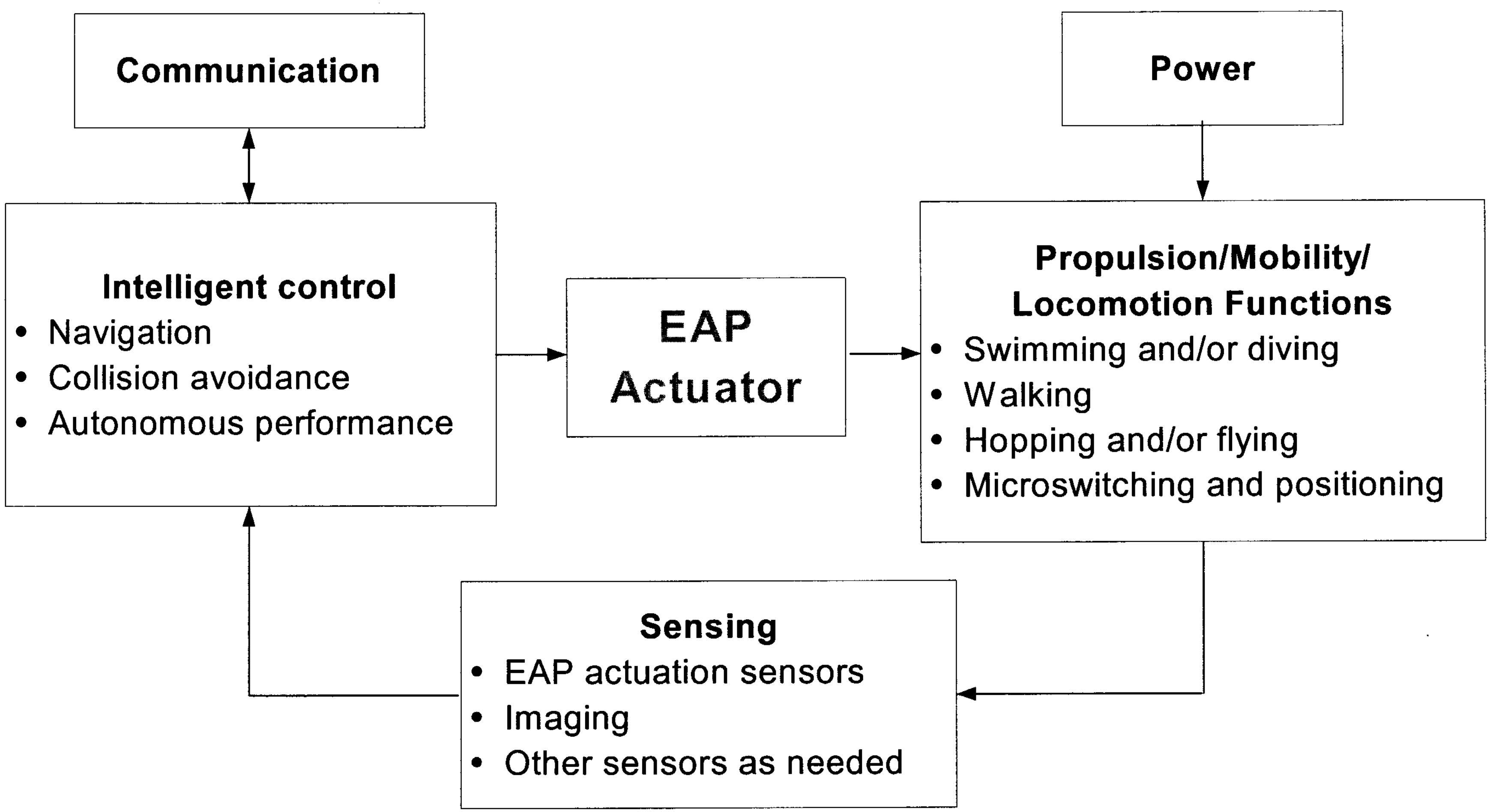
Lemur - 6-legged robots at JPL

Robot that responds to human expressions

Cynthia Breazeal and her robot Donna



Elements of an EAP actuated robots



Background

- Most conventional mechanisms are driven by actuators requiring gears, bearings, and other complex components.
- Emulating biological muscles can enable various novel manipulation capabilities that are impossible today.
- Electroactive polymers (EAP) are emerging with capability that can mimic muscles to actuate biologically inspired mechanisms.
- EAP are resilient, fracture tolerant, noiseless actuators that can be made miniature, low mass, inexpensive and consume low power.
- EAP can potentially be used to construct 3-D systems, such as robotics, which can be imagined today as science fiction.

Comparison between EAP and widely used transducing actuators

Property	EAP	EAC	SMA
Actuation strain	>10%	0.1 - 0.3 %	<8% short fatigue life
Force (MPa)	0.1 – 3	30-40	about 700
Reaction speed	μsec to sec	μsec to sec	sec to min
Density	1- 2.5 g/cc	6-8 g/cc	5 - 6 g/cc
Drive voltage	2-7V/ 10-100V/μm	50 - 800 V	NA
Consumed Power*	m-watts	watts	watts
Fracture toughness	resilient, elastic	fragile	elastic

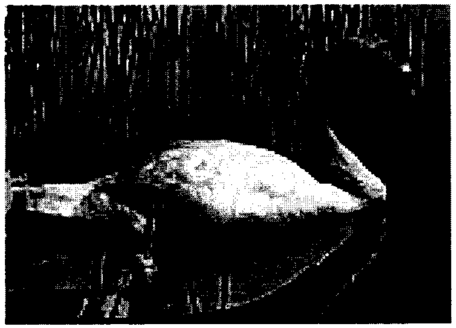
* Note: Power values are compared for documented devices driven by such actuators.

BIOLOGICALLY INSPIRED ROBOTICS

IN-SITU MULTI-TASKING MISSIONS USING SCALABLE AUTONOMOUS ROBOTS FOR COLONIZED EXPLORATION

Multiple locomotion capabilities

Flying,
walking,
swimming &
diving



Hopping,
flying,
crawling
& digging

Models for EAP Actuated Flexible Robots

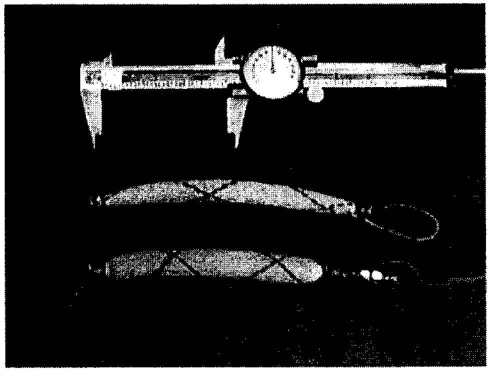
Coordinated robotics

Neural networks
& expert systems

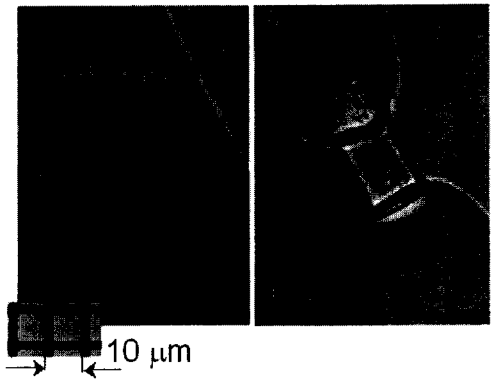
Non-Electro Active Polymers (NEAP)

- Conductive and Photonic Polymers
- Smart Structures and Materials
- Deformable Polymers
  - Chemically Activated
  - Shape Memory Polymers
  - Inflatable Structures
  - Light Activated Polymers
  - Magnetically Activated Polymers

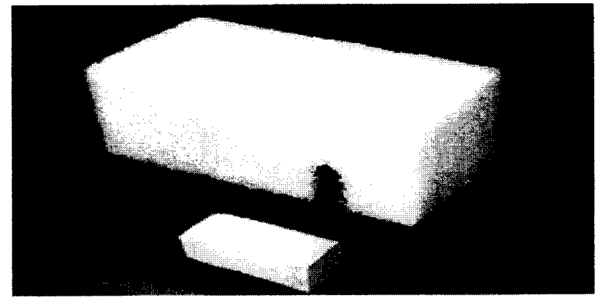
Non-electrical mechanically activated polymers



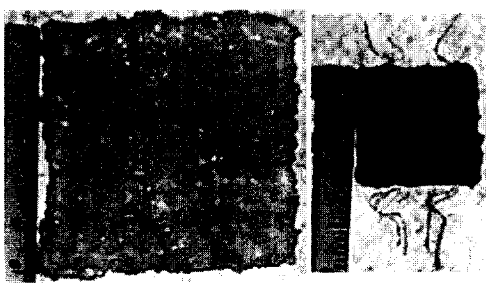
McKibben Artificial Muscles
Air Pressure activation
(Hannaford, B.U. Washington)



Laser Illuminated Polymer
Light activation (H. Misawa, Japan)



Shape Memory Polymers
Heat/pressure activation (W. Sokolowski, JPL)



Ionic Gel Polymers
Chemical transduction (P. Calvert, UA)

Ferrogel
Magnetic Activation (M. Zrinyi, Hungary)

Smart Structures
Polymers with Stable shapes
(S. Poland, Luna Innovations, VA
)

Historical prospective

- Roentgen [1880] is credited for the first experiment with EAP electro-activating rubber-band to move a cantilever with mass attached to the free-end
- Sacerdote [1899] formulated the strain response of polymers to electric field activation
- Eguchi [1925] discovery of electrets* marks the first developed EAP
  - Obtained when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field.
- Another important milestone is Kawai [1969] observation of a substantial piezoelectric activity in PVF2.
  - PVF2 films were applied as sensors, miniature actuators and speakers.
- Since the early 70's the list of new EAP materials has grown considerably, but the most progress was made after 1990.

* Electrets are dielectric materials that can store charges for long times and produce field variation in reaction to pressure.

Electroactive Polymers (EAP)

ELECTRONIC EAP

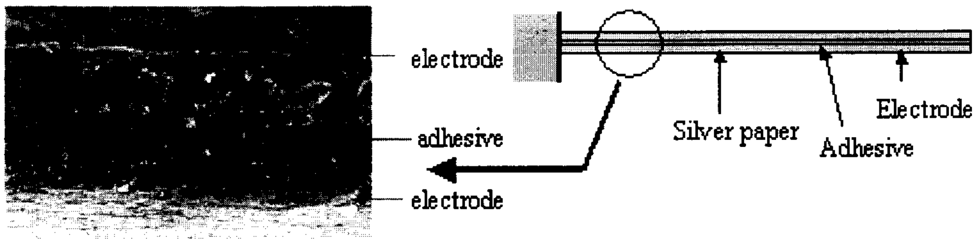
- Dielectric EAP
- Electrostrictive Graft Elastomers
- Electrostrictive Paper
- Electro-Viscoelastic Elastomers
- Ferroelectric Polymers
- Liquid Crystal Elastomers (LCE)

IONIC EAP

- Carbon Nanotubes (CNT)
- Conductive Polymers (CP)
- ElectroRheological Fluids (ERF)
- Ionic Polymer Gels (IPG)
- Ionic Polymer Metallic Composite (IPMC)

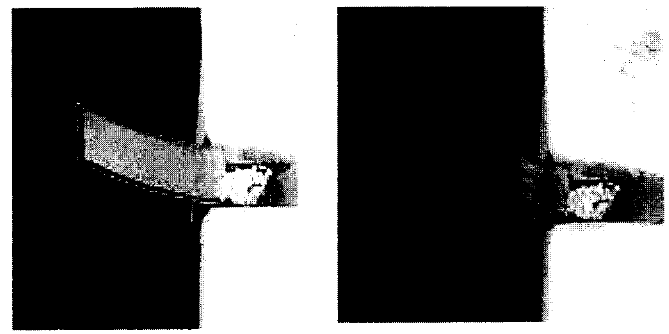
Electronic EAP

ELECTRIC FIELD OR COULOMB FORCES DRIVEN ACTUATORS



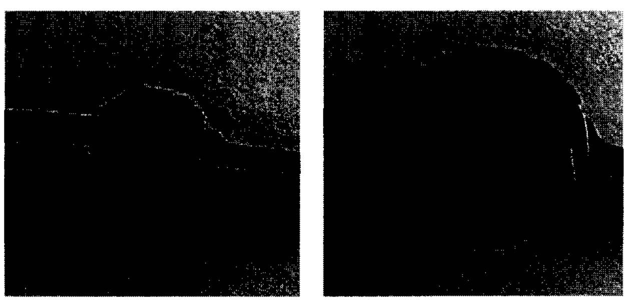
Paper EAP

[J. Kim, Inha University, Korea]



Ferroelectric

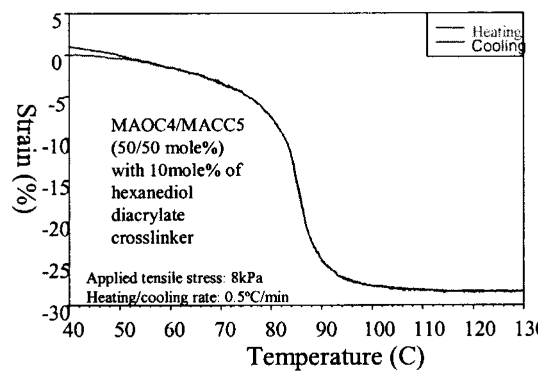
[Q. Zhang, Penn State U.]



Voltage Off **Voltage On**

Dielectric EAP

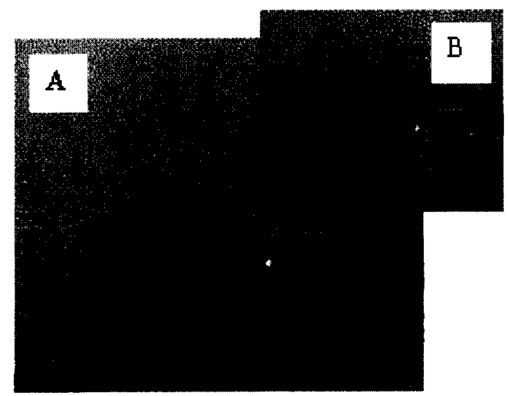
[R. Kornbluh, et al., SRI International]



Liquid crystals

(Piezoelectric and thermo-mechanic)

[B. R. Ratna, NRL]

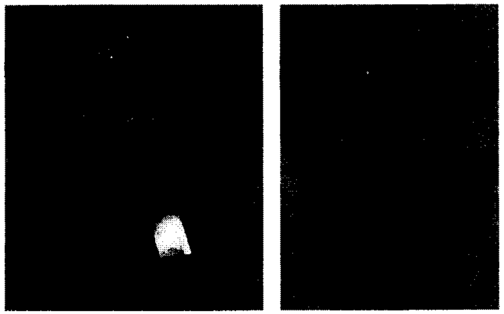


Graft Elastomer

[J. Su, NASA LaRC]

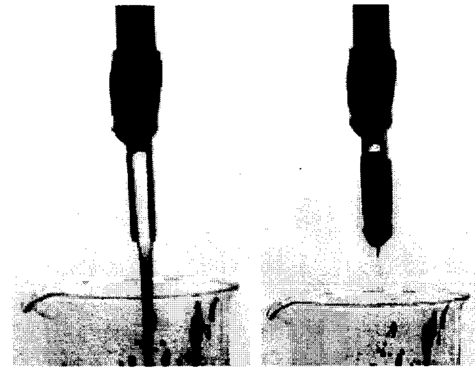
Ionic EAP

Turning chemistry to actuation



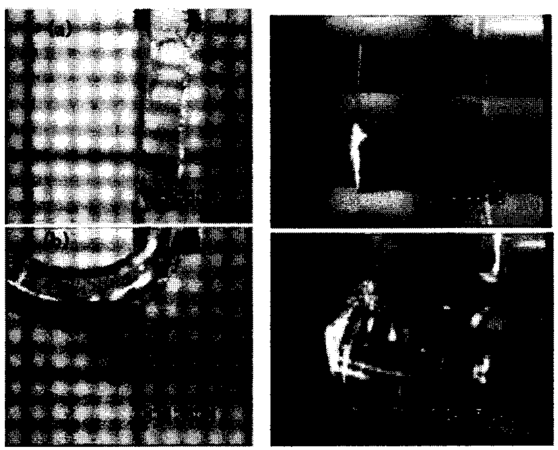
IPMC

[JPL using ONRI, Japan & UNM materials]



ElectroRheological Fluids (ERF)

[ER Fluids Developments Ltd]

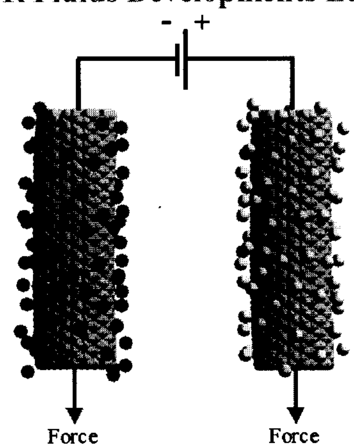


t = 0 s

t = 1.1 s

Ionic Gel

[T. Hirai, Shinshu University, Japan]



Carbon-Nanotubes

[R. Baughman et al, Honeywell, et al]

Current EAP
Advantages and disadvantages

EAP type	Advantages	Disadvantages
Electronic EAP	· Can operate in room conditions for a long time · Rapid response (mSec levels) · Can hold strain under DC activation · Induces relatively large actuation forces	· Requires high voltages (~150V/μm) · Requires compromise between strain and stress · Glass transition temperature is inadequate for low temperature actuation tasks
Ionic EAP	· Large bending displacements · Provides mostly bending actuation (longitudinal mechanisms can be constructed) · Requires low voltage	· Except for CPs, ionic EAPs do not hold strain under DC voltage · Slow response (fraction of a second) · Bending EAPs induce a relatively low actuation force · Except for CPs, it is difficult to produce a consistent material (particularly IPMC) · In aqueous systems the material sustains hydrolysis at >1.23-V

Applications of EAP to potential planetary tasks

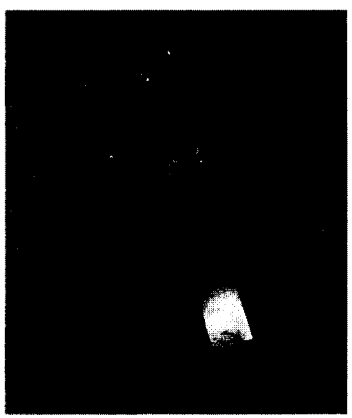
Considered planetary applications

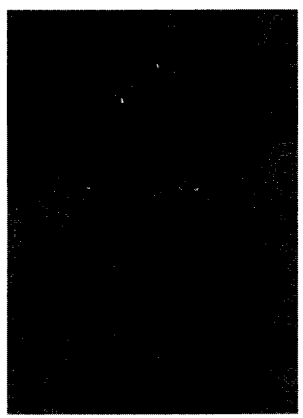
Dust wiper

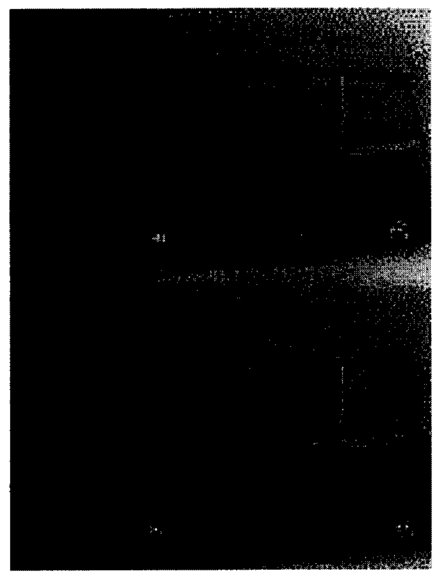
Bending EAP is used as a surface wiper

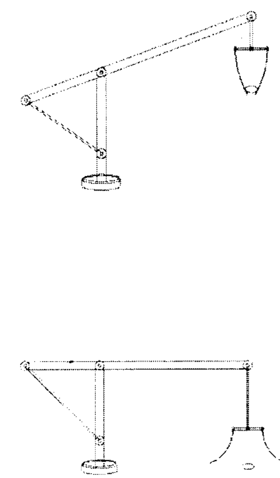
Sample handling robotics

Extending EAP lowers a robotic arm, while bending EAP fingers operate as a gripper



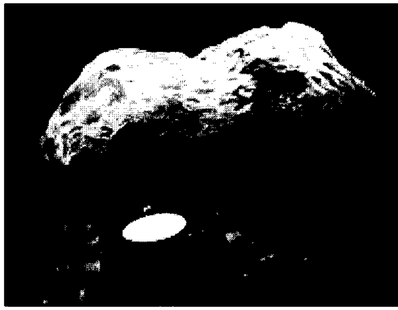




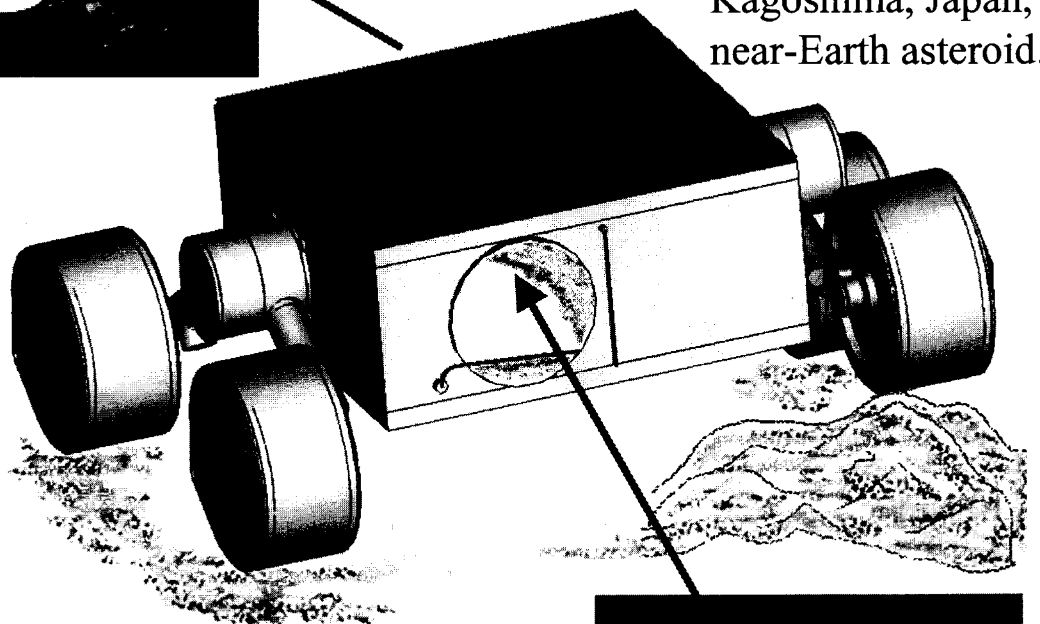


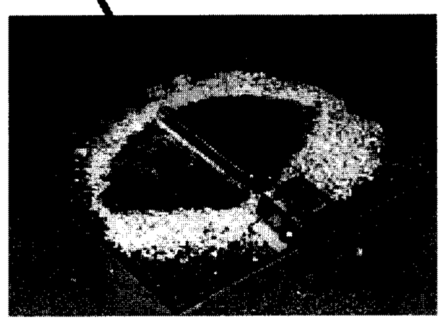
EAP Dust Wiper

for the MUSES-CN Nanorover



MUSES-CN mission was a joint NASA and NASDA (National Space Development Agency of Japan) mission scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid.



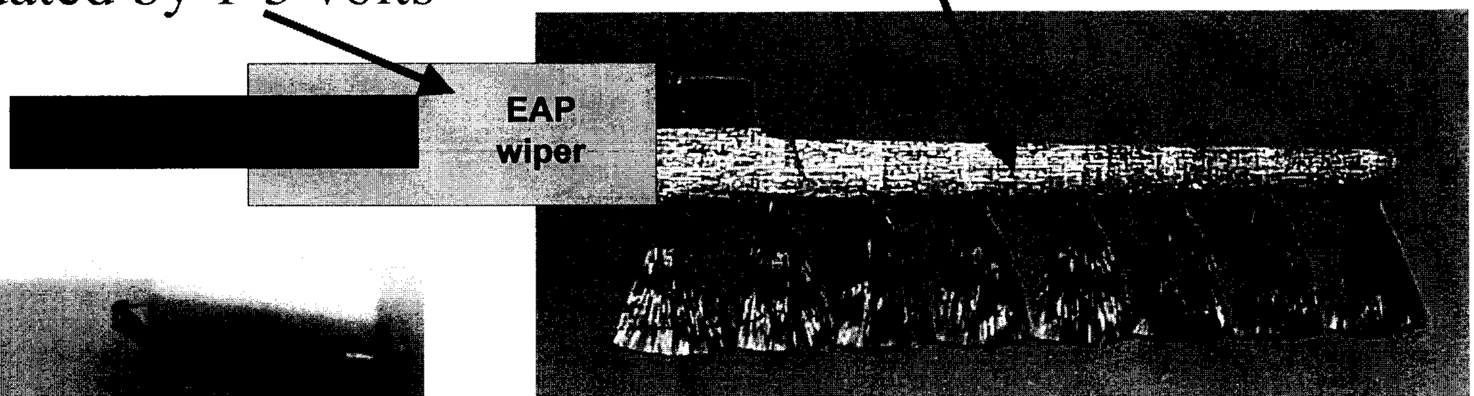


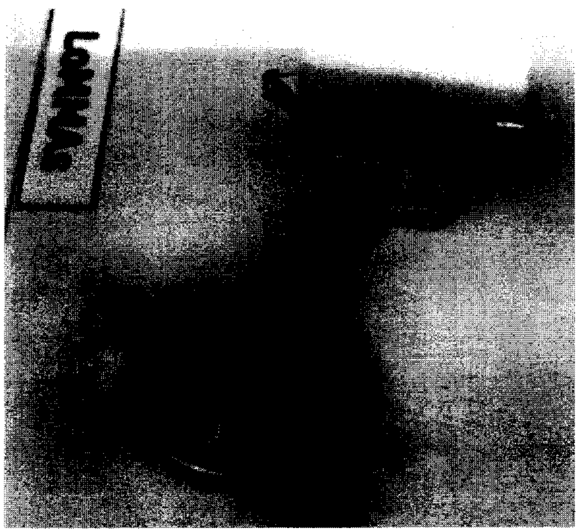
- An IPMC actuated wiper was selected as a baseline for the dust removal from the visual/IR window.
- The technical challenges were beyond the technology readiness requirements
- Due to budget constraints, this mission was cancelled in Nov. 2000.

Surface wiper activated by EAP

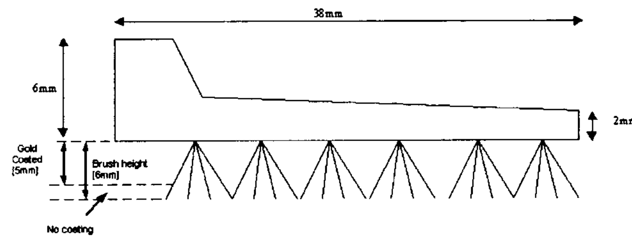
Actuated by 1-3 volts

Biased with 1-2KV for dust repulsion





Graphite/Epoxy wiper blade* with fiberglass brush coated with gold



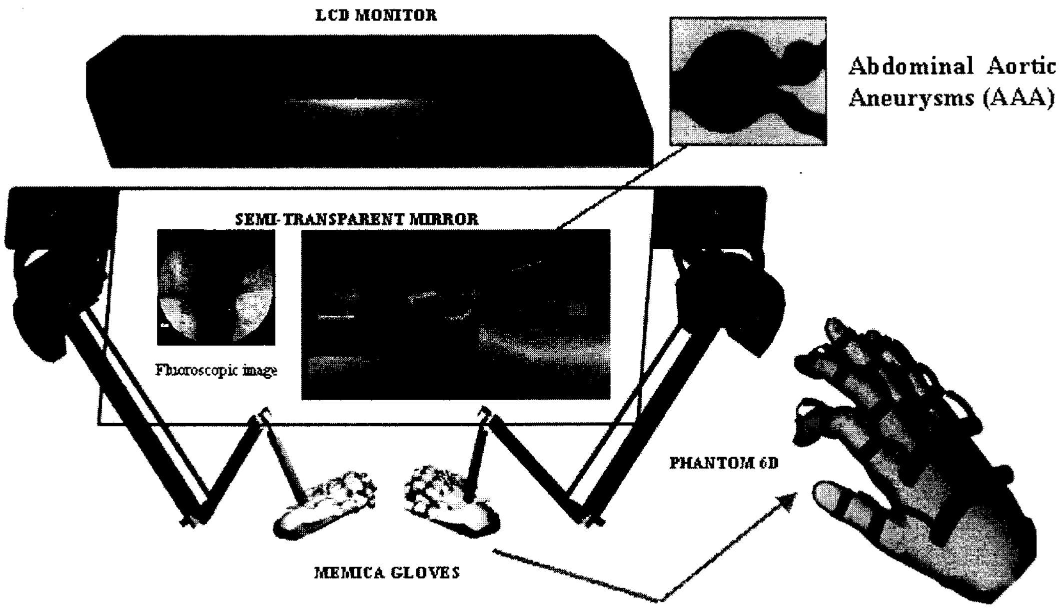
* Made by Energy Science Laboratories, Inc., San Diego, California

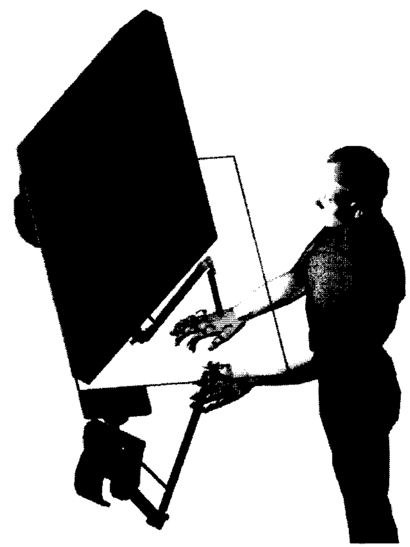
Challenges and solutions to the application of IPMC as bending actuators

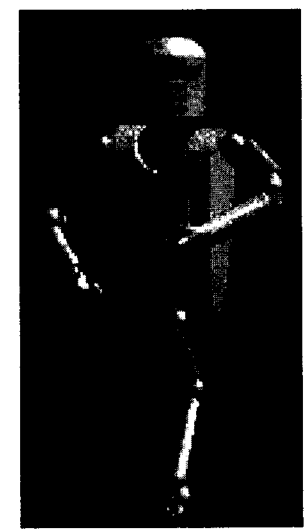
Challenge	Potential Solution
Fluorinate base - difficult to bond	Etching the surface makes it amenable to bonding
Extremely sensitive to dehydration	Apply protective coating over the etched IPMC
Off-axis bending actuation	Constrain the free end and use a high ratio of length/width
Operate at low temperatures	IPMC was demonstrated to respond at -100°C in vacuum
Remove submicron dust	Use effective wiper-blade design and high bias voltage
Reverse bending drift under DC voltage	Limit the operation to cyclic activation to minimize this effect, and use cations such as Li^+ rather than Na^+.
Protective coating is permeable	Develop alternative coating, possibly using multiple layers
Electrolysis occurs at >1.23-V	Use efficient IPMC that requires low actuation voltage
Residual deformation particularly after intermittent activation	It occurs mostly after DC or pulse activation and it remains a challenge
Difficulties to assure material reproducibility	Still a challenge. May be overcome using mass production and protective coating.
Degradation with time due to loss of ions to the host liquid	Requires electrolyte with enriched cation content of the same species as in the IPMC

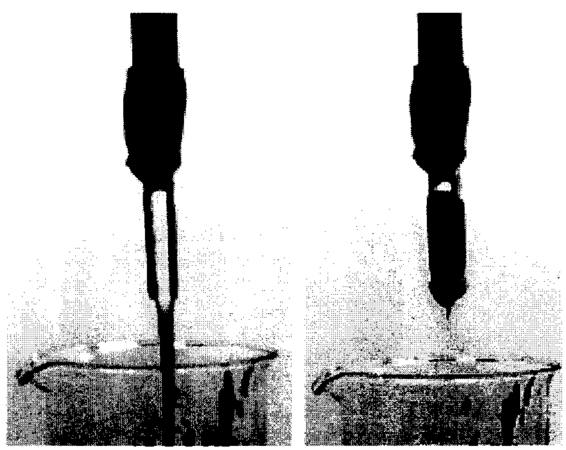
MEMICA

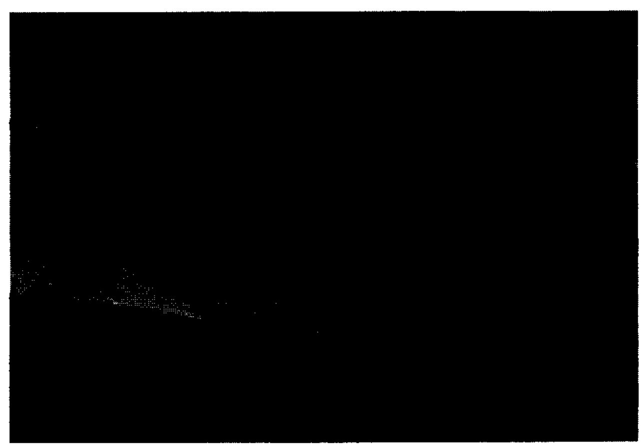
(MEchanical MIrroring using Controlled stiffness and Actuators)

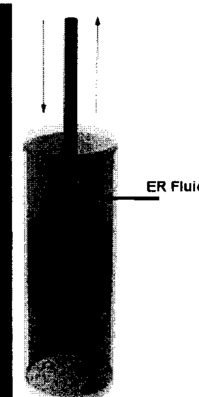


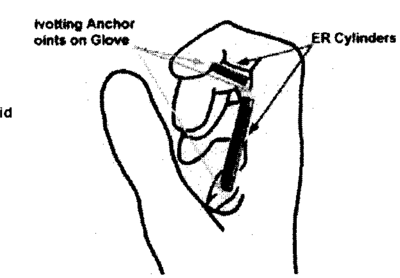












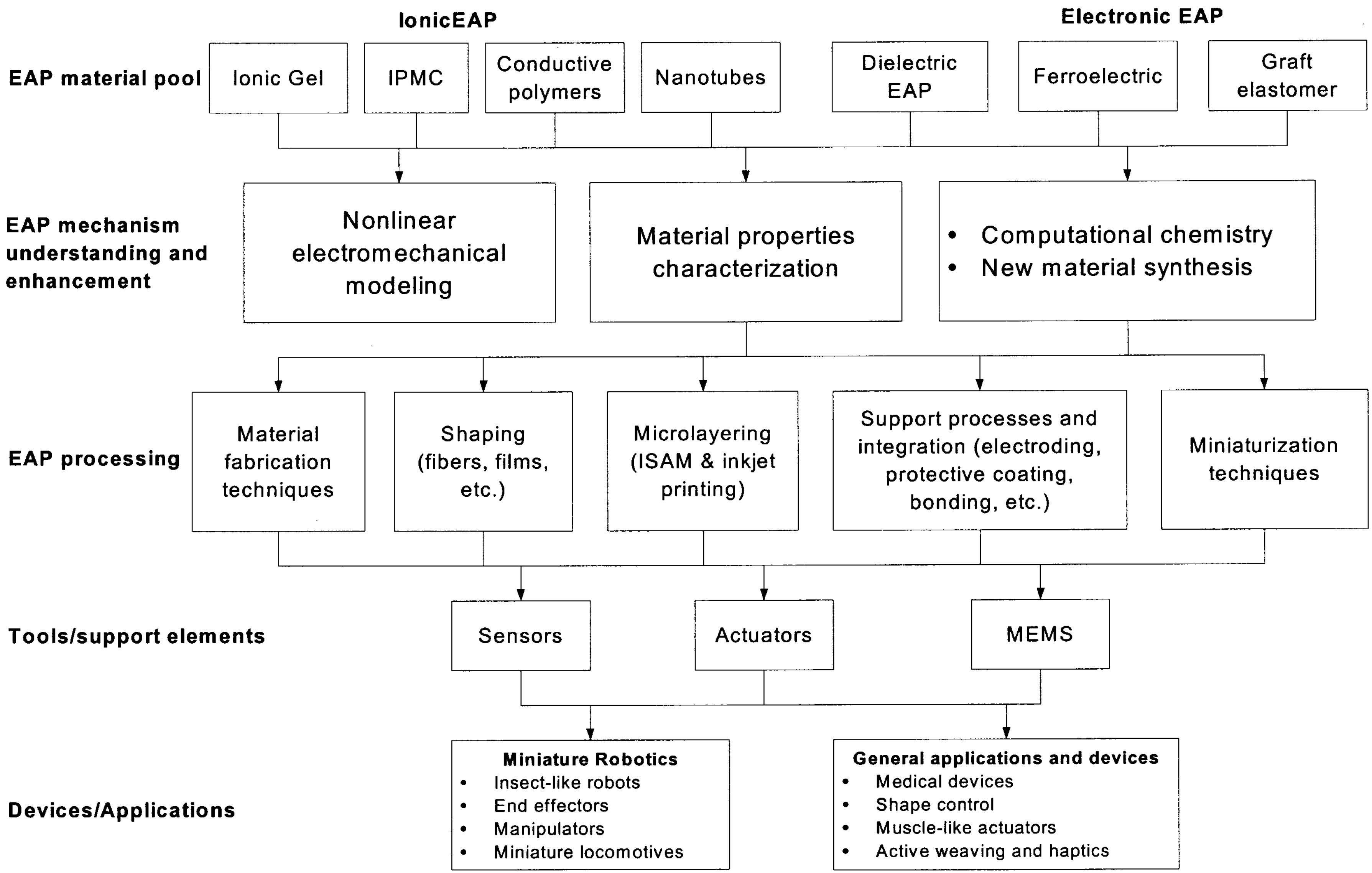
Electro-Rheological Fluid at reference (left) and activated states (right). [Smart Technology Ltd, UK]

MEMICA-based exoskeleton for countermeasure of astronauts bones and muscles loss in microgravity. It has potential application as:

- Assist patient rehabilitation
- Enhance human mobility

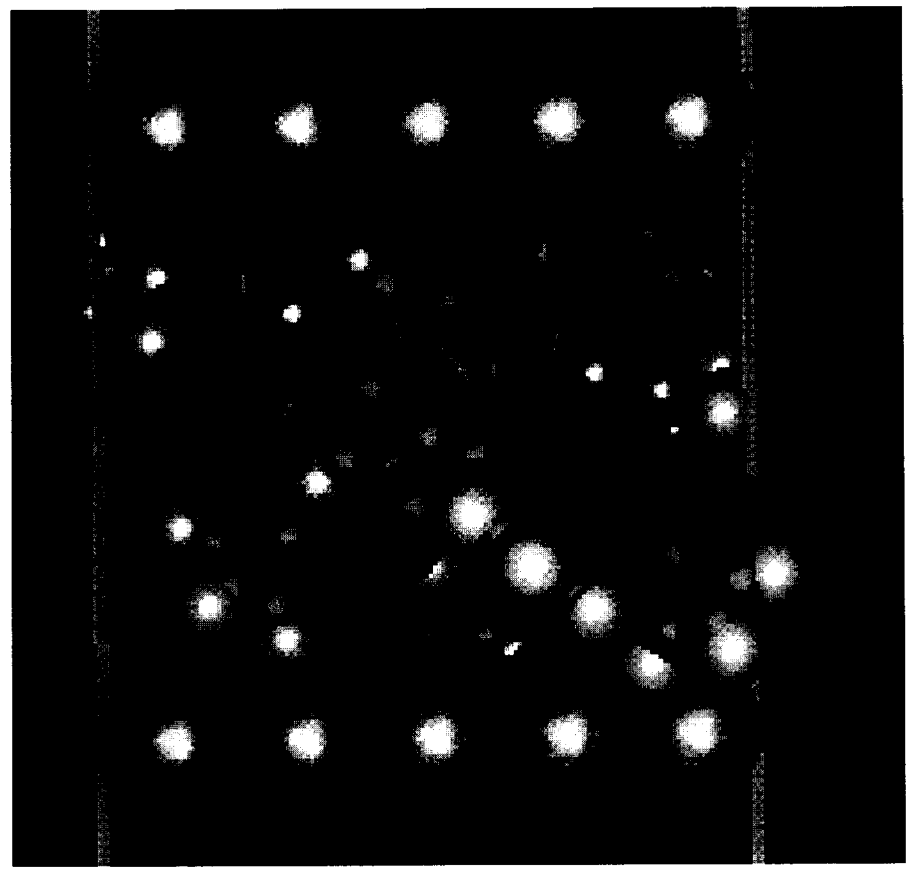
Elements of the EAP Infrastructure

EAP infrastructure



Computational chemistry

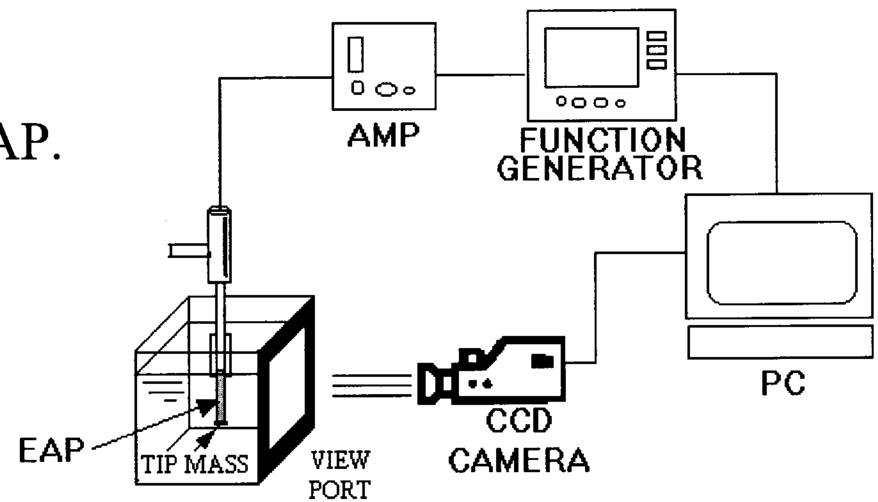
Computational chemistry may lead to material design tools using comprehensive modeling to methodically synthesize effective new EAPs

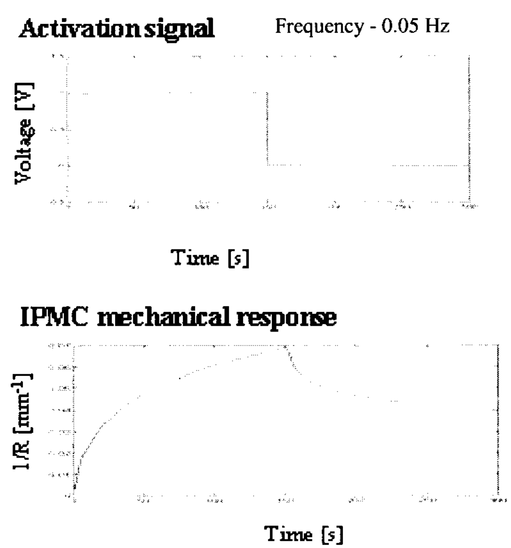


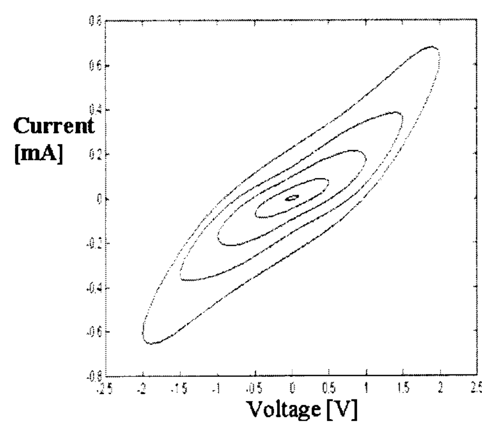
(NASA-LaRC)

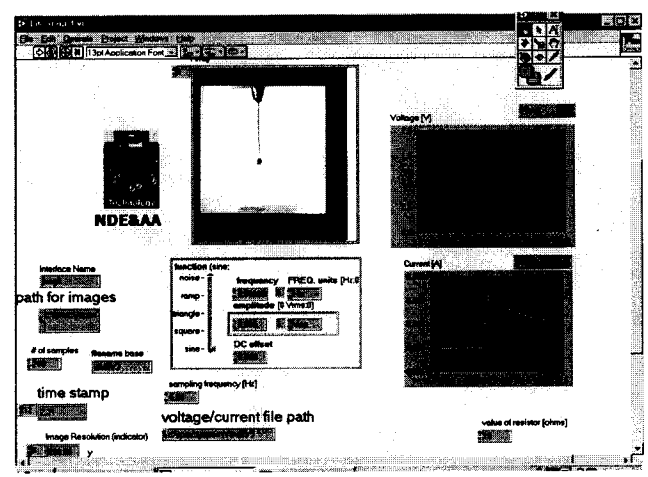
EAP Material Characterization

- Different methods of characterization are needed for the various types of EAP.
- Efforts are underway to develop a database that allows comparing with properties of other actuators









Applications

Underway or under consideration

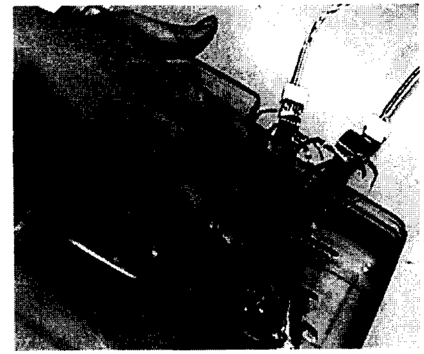
- **Mechanisms**
  - Lenses with controlled configuration
  - Mechanical Lock
  - Noise reduction
  - Flight control surfaces/Jet flow control
  - Anti G-Suit
- **Robotics, Toys and Animatronics**
  - Biologically-inspired Robots
  - Toys and Animatronics
- **Human-Machine Interfaces**
  - Haptic interfaces
  - Tactile interfaces
  - Orientation indicator
  - Smart flight/diving Suits
  - Artificial Nose
  - Braille display (for Blind Persons)
- **Planetary Applications**
  - Sensor cleaner/wiper
  - Shape control of gossamer structures
- Medical Applications
  - EAP for Biological Muscle Augmentation or Replacement
  - Miniature in-Vivo EAP Robots for Diagnostics and Microsurgery
  - Catheter Steering Mechanism
  - Tissues Growth Engineering
  - Interfacing Neuron to Electronic Devices Using EAP
  - Active Bandage
- Liquid and Gases Flow Control
- Controlled Weaving
  - Garment and Clothing
- MEMS
- EM Polymer Sensors &Transducers

Human-Machine Interfaces

- Interfacing human and machine to complement or substitute our senses would enable important medical applications.

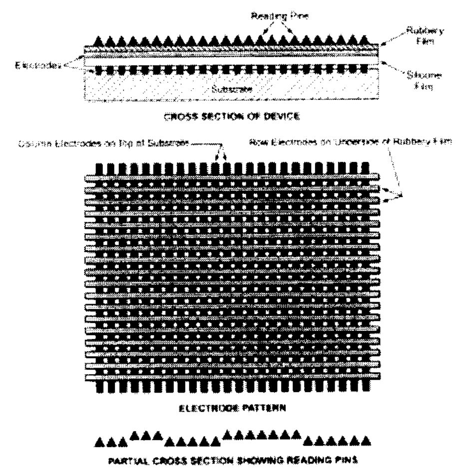
- Researchers at Duke U. connected electrodes to a brain of a money and were able to control a robotic arm. This breakthrough opens the possibility that the human brain would be able to operate prosthetics that are driven by EAP.

- Feedback is required to "feel" the environment around the artificial limbs. Currently, researchers are developing tactile sensors, haptic devices, and other interfaces.



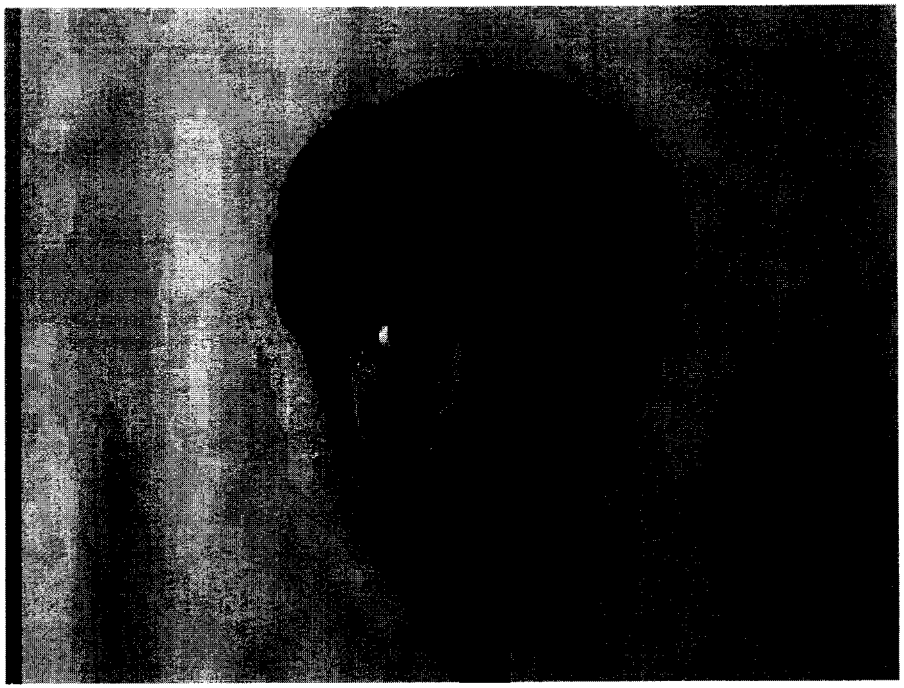
Tactile Interface

(S. Tadokoro, Kobe U., Japan)



Active Braille Display

Platforms for EAP Implementation



Android making facial expressions

[Sculptured by D. Hanson, U. of Texas, Dallas, and instrumented by jointly with G. Pioggia, University of Pisa, Italy]

Robotic hand platform for EAP

[G. Whiteley, Sheffield Hallam U., UK]

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WW-EAP Newsletter

- **http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html**

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Transducing materials play an important role in our daily life being responsible for the functionality of many instruments and devices that are commonly used. New materials are continuing to emerge,

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SUMMARY

- Artificial technologies (AI, AM, and others) for making biologically inspired devices and instruments are increasingly being commercialized.
  - Autonomous robotics, wireless communication, miniature electronics, effective materials, powerful information technology are some of the critical support technologies that have evolved enormously in recent years.
- Materials that resemble human and animals are widely used by movie industry and animatronics have advanced to become powerful tools.
- Electroactive polymers are human made actuators that are the closest to resemble biological muscle potentially enabling unique robotic capabilities.
- Technology has advanced to the level that biologically inspired robots are taking increasing role making science fiction ideas closer to an engineering reality.

The grand challenge for EAP as Artificial Muscles